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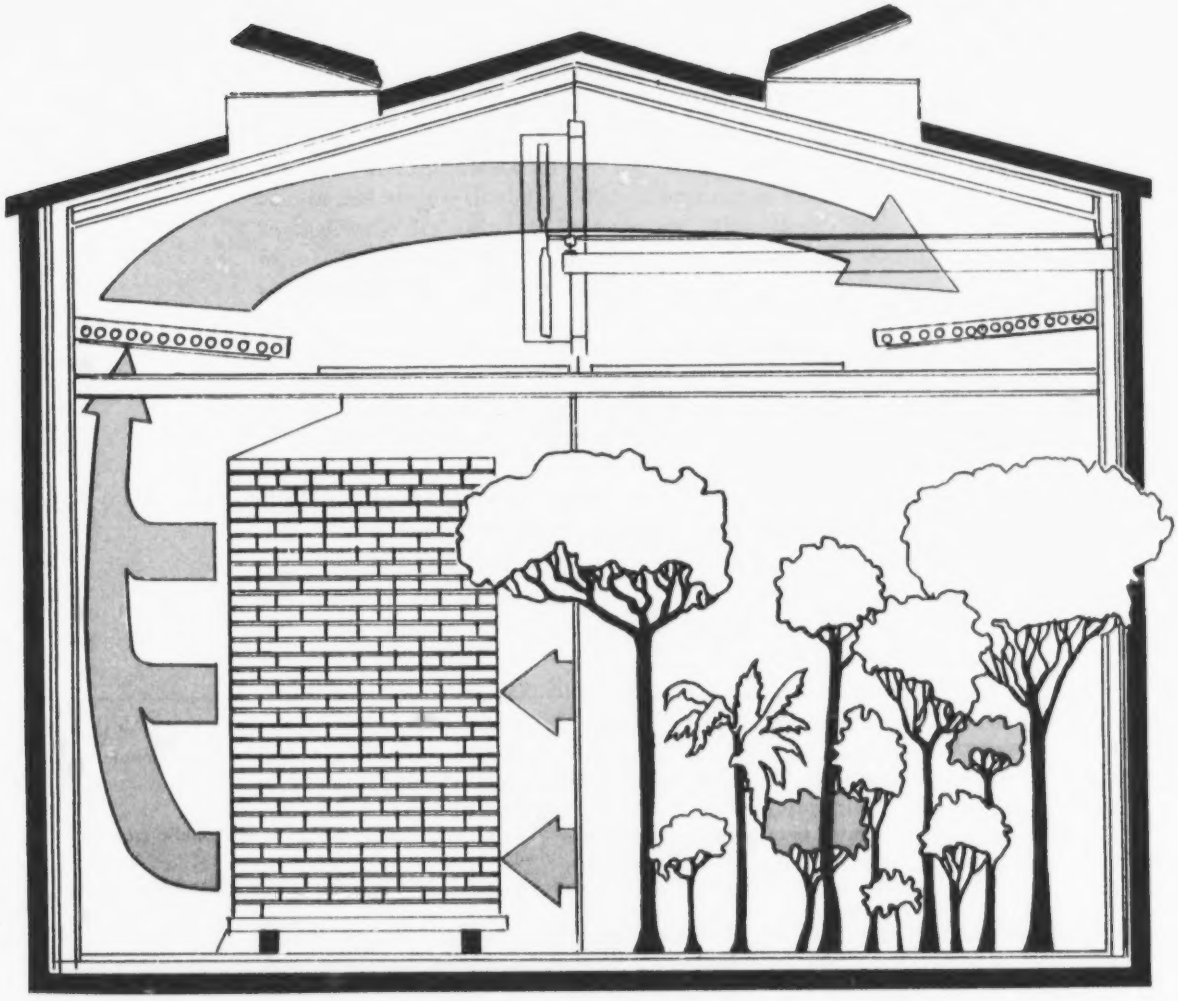
Grouping Tropical Wood Species for Kiln Drying

William T. Simpson
Charlie K. Baah



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Abstract

The most efficient method to kiln dry tropical hardwood species is in groups because of the large number of them and their diffuse occurrence in the forest. However, this large number of species presents a wide variety of drying properties, which makes it difficult to dry mixtures of species. This report develops a mathematical model for grouping species by similar drying times. The goal is to kiln dry so all species will emerge from the same kiln at the same time within set limits of moisture content and with minimum drying defects. The model, which utilizes experimental drying rate data collected in previously reported research, incorporates specific gravity and initial moisture content as criteria for grouping species based on estimated drying time. The model has not been tested in actual kiln drying studies but establishes the necessary framework to design such a study.

Keywords: Kiln drying, drying, tropical hardwoods

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Grouping Tropical Wood Species for Kiln Drying

William T. Simpson, Research Forest Products Technologist
USDA Forest Service
Forest Products Laboratory
Madison, Wisconsin

Charlie K. Baah, Graduate Student
SUNY College of Environmental
Science and Forestry
Syracuse, New York

Introduction

Drying characteristics of wood depend on certain wood properties. Species variation of properties such as specific gravity, green moisture content, extractives content, and anatomical elements affects drying behavior. The most important responses of wood to drying are susceptibility to drying defects and drying rate. If these two responses did not vary by species, different kiln schedules for different species would not be needed, and drying mixtures of species would present few problems. One schedule would minimize drying defects, drying time, and energy consumption for all species. The problems of drying mixtures of tropical species are particularly difficult because of the large number of species and their diverse drying-related properties. Also, their diffuse occurrence in tropical forests favors harvesting and processing systems that deal with mixtures rather than segregations by individual species.

The objective of this report is to describe a method to group species according to similar estimated drying times so that they could be dried in the same kiln charge and emerge from the kiln at the same time within set limits of final moisture content.

Background

Although kiln schedules have been developed for many tropical species (Boone and others 1988) and included with other information and properties (Chudnoff 1984), not many reports are available on drying mixtures of species. In most of the attempts reported, some or all of the properties that influence drying behavior were considered in developing the groupings. One difficulty in establishing grouping criteria is the availability of or ease of determining a quantitative measure of the property. Specific gravity affects drying behavior—species with high specific gravity generally dry more slowly and are more susceptible to drying defects than species with low specific gravity. Initial moisture content affects drying time—species with high initial moisture content require longer drying times. An interactive effect of specific gravity and initial moisture content is likely, but it is not well defined. Specific gravity and initial moisture content data are available for many species or are relatively easy to determine.

Other factors that affect either drying time or susceptibility to drying defects are not as available, determined as easily, or used. Permeability to fluid flow, transverse shrinkage, ratio of tangential to radial shrinkage, longitudinal

shrinkage, strength, irregular grain patterns, heartwood or sapwood, extractives content, and details of wood anatomy (such as the volume and size of wood rays and vessels) all affect drying behavior. Although all these factors are important, and even limiting in some cases, they are either difficult to measure or difficult to incorporate into a grouping system.

Bello (1966) grouped 23 Philippine species into three classes based on their ease of drying. The first group contained species that were considered easy to dry, the second group contained those that were considered moderately slow to dry, and the third group comprised those species that were considered difficult to dry. Casin and others (1980) grouped 60 Philippine species into four groups based on the drying characteristics of the species as well as the experience of knowledgeable kiln operators. The characteristics they considered were density, grain characteristics, and shrinkage.

Ma (1970, 1972, 1973, 1974, 1975a,b) developed five time-based kiln schedules for mixtures of 80 Taiwan hardwoods. Drying rates, surface drying stresses, uniformity of final moisture content, shrinkage, and drying defects were considered. They recommended that these schedules could be used for other tropical species whose characteristics are similar to those of the species in the five groups. Although these schedules covered only drying from green to 25 percent moisture content, the author believed the schedules could be expanded into drying below 25 percent moisture content.

Keenan and Tejada (1984) summarized research on air drying, kiln schedules, drying times, and type and severity of drying defects for 105 South American species. Based on this research, three drying schedules of progressive severity were proposed for these species.

Samad and Wallin (1966) and Ali and others (1968) developed five kiln schedules intended for drying mixtures of species native to Bangladesh. Their grouping was based on a mathematical model that related drying time to temperature and specific gravity. Initial moisture content also entered into the model and was approximated by the empirically determined relationship,

$$W_0 = \left(\frac{1 - 0.65G}{G} \times 100\right)[1 - \exp(-1.573G - 3.089G^2)] \qquad (1)$$

where W_0 is initial moisture content (percent) and G is specific gravity.

Each of these five schedules covered different ranges of specific gravity and included from 7 to 17 separate temperature and relative humidity steps. The grouping system is well conceived and based on valid experimental data. It does, however, depend on the approximate initial moisture content-specific gravity relationship (Eq. (1)), and this grouping system will not apply to species that do not follow this relationship or that have undergone some air drying before entering the kiln.

Durand (1985) conducted an analysis to show the relationship between certain physical properties of wood and drying behavior, and to develop a way to establish kiln schedules from these data. The analysis did not include estimated

drying time, and it was built on the sensitivity to drying defects. Using these property data for 25 Ivory Coast species and knowing the temperature and equilibrium moisture content (EMC) conditions, he developed multiple regression equations that related the temperature and EMC schedules (established by experience) to four properties. These four properties were density, total volumetric shrinkage, volumetric shrinkage coefficient between the wood moisture content and air-dry EMC, and the ratio of tangential-to-radial shrinkage. Durand then used this relationship to estimate the kiln schedule for other Ivory Coast species whose kiln schedules had not been established by experience. He did not test the derived schedules on these additional species but noted that experiments to test the grouping method were planned.

Based on information in the literature, it appears that specific gravity and initial moisture content are the most influential and easily defined variables for establishing species groupings based on estimated drying time. These variables do not address the susceptibility to drying defects, but no practical quantitative procedure has been developed to combine grouping on this basis with grouping on a drying-time basis. Even without this quantitative information on drying defects, an initial approach to drying mixtures of species can be developed based on similar estimated drying times. Conservative schedules can be developed that will not damage most species. Although this approach to grouping will result in some inefficiencies with the species that could be dried by a more severe schedule, it is probably more efficient than segregations by individual species. The approach can also be considered as a starting point to be modified with experience.

Method for Grouping Species

Mathematical Model

The method for grouping species is based on a mathematical model that estimates drying time as it depends on specific gravity, initial moisture content, temperature, relative humidity, and board thickness. Species that have similar estimated drying times can then be dried together by a relatively conservative kiln schedule that is not likely to cause excessive drying defects. The details of the model development are given in Tschernitz and Simpson (1977) and Simpson and Tschernitz (1980). It is based on the assumption that drying rate is proportional to average moisture content. The final equation can be stated in the form

$$t = \frac{-L^{1.52}}{b_s} \frac{b_{T_1}}{b_{T_2}} \ln\left(\frac{W_a - W_e}{W_0 - W_e}\right) \qquad (2)$$

where

t is time (days),
L board thickness (in.),
b_s empirical coefficient for effect of specific gravity,
b_{T_1} empirical coefficient for effect of temperature at temperature $T_1 = 120°F$,
b_{T_2} empirical coefficient for effect of temperature at any temperature T_2 between 100°F and 180°F,
W_a average moisture content (percent) at time t, and
W_e equilibrium moisture content conditions in kiln (percent).

The b coefficients were determined as described in Tschernitz and Simpson (1977). In that experiment, $T_1 = 120°F$ (49°C). The coefficient b_s was determined for 43 Philippine species at T_1, and was related to specific gravity as shown in Figure 1. Regression analysis results in the following relationship between b_s and specific gravity (Tschernitz and Simpson 1977):

$$b_s = 0.0104 + \frac{0.133}{G} \tag{3}$$

The ratio of b_{T_1} to b_{T_2} adjusts b_s for temperatures other than 120°F (49°C), and the relationship between them and temperature and humidity is (Simpson and Tschernitz 1980)

$$b_T = 0.0575 + 0.00142p \tag{4}$$

where p is the vapor pressure of water in millimeters mercury within the temperature range of 100°F (38°C) to 180°F (82°C), and

$$p = \exp\left(20.41 - \frac{5132}{T}\right) \tag{5}$$

where T is in kelvins.

Combining Equations (4) and (5), b_{T_1} and b_{T_2} are calculated by

$$b = 0.0575 + 0.00142\exp\left(20.41 - \frac{5132}{T}\right) \tag{6}$$

Equation (2) can thus be written as

$$t = \frac{-L^{1.52}}{0.0104 + 0.133/G}\frac{b_{T_1}}{b_{T_2}}\ln\left(\frac{W_a - W_e}{W_0 - W_e}\right) \tag{7}$$

Other convenient forms of Equation (7) that are used in the grouping method are

$$G = \frac{0.133tb_{T_2}}{-L^{1.52}b_{T_1}\ln[(W_a - W_e)/(W_0 - W_e)] - 0.0104tb_{T_2}} \tag{8}$$

and

$$W_a = [\exp(t/c)](W_0 - W_e) + W_e \tag{9}$$

where

$$c = \frac{-L^{1.52}}{0.0104 + 0.133/G}\frac{b_{T_1}}{b_{T_2}} \tag{10}$$

The model cannot deal with the presence of tyloses, which will cause a decrease in drying rate, but fortunately few tropical species contain tyloses.

Description and Example of Grouping Method

The grouping method is based on determining combinations of specific gravity and initial moisture content that result in equal drying times. For example, the model as described by Equations (7) to (10) predicts that 11 days are required to dry 1.125-in.- (29-mm-) thick lumber from green to 30 percent moisture content at 100°F (38°C) and 14 percent EMC when initial moisture content is 120 percent and specific gravity is 0.472, and also when initial moisture content is 60 percent and specific gravity is 0.870. Graphs of equal drying times as a function of specific gravity and initial moisture content can be constructed for any combination of drying temperature, EMC conditions, final moisture content, and thickness. This is done by first selecting the desired temperature (T_2), EMC conditions (W_e), final moisture content (W_a), and thickness (L). The initial moisture content W_0 and time t can be varied, and the corresponding values of specific gravity calculated with Equation 8. Figure 2 shows an example at 100°F (38°C), 14 percent EMC, 30 percent final moisture content, and 1.125-in. (29-mm) thickness.

An example will help clarify the grouping and drying method. Assume we have a number of species of various specific gravities and initial moisture contents and that we either know both or can determine them. If specific gravity is known but initial moisture content is not, it can be estimated from Equation (1). Further assume that we will use a conservative schedule, such as the one shown in Figure 2, where 1.125-in.- (29-mm-) thick lumber is dried from green to 30 percent moisture content at 100°F (38°C) and 14 percent EMC (78 percent relative humidity). Ideally we would have enough species with combinations of specific gravity and initial moisture content with equal drying times so that they could be efficiently grouped. Because this is unlikely, grouping species with combinations of specific gravity and initial moisture content that fall within a range of times is more practical. In this example we will make a grouping where the drying times to 30 percent moisture content range from 9 to 12 days. We will select the following eight combinations (Fig. 2), all of which result in calculated drying times (Eq. (7)) that are between 9 and 12 days:

Specific gravity	Initial moisture content (percent)
0.40	120
0.50	90
0.53	110
0.61	90
0.68	65
0.75	70
0.88	61
0.93	50

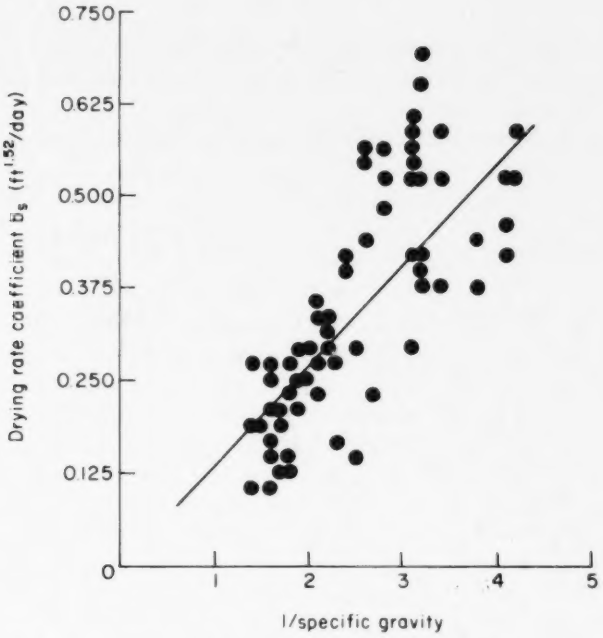

Figure 1 — Correlation of drying rate coefficient b_s to specific gravity at 120° F (49° C). (ML89 5652)

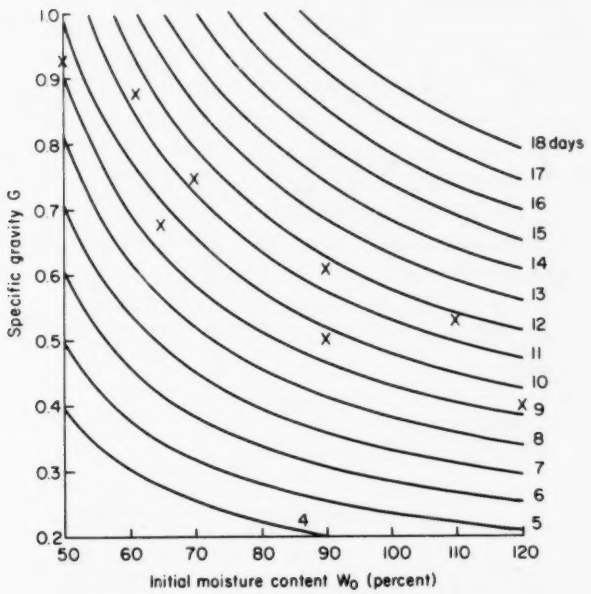

Figure 2 — Combinations of specific gravity and initial moisture content that result in equal drying times for 1.125-in.- (29-mm-) thick lumber at 100° F (38° C). (Final average moisture content W_a = 30 percent; EMC, W_e = 14 percent.) (ML89 5653)

Table 1—Example of a conservative three-step kiln schedule

Moisture content interval (percent)	Drying temperature T_2 (°F (°C))	EMC[a] (percent)	Relative humidity (percent)	Wet-bulb temperature T_w (°F (°C))
Green – 30	100 (38)	14	78	93 (34)
30 – 20	120 (49)	12	71	110 (43)
20 – 10	160 (71)	6	44	131 (55)
Equalization	160 (71)	10	70	147 (64)

[a]EMC is equilibrium moisture content.

The next step is to choose a kiln schedule. The drying times shown in Figure 2 are with a single-step schedule from green to a final moisture content of 30 percent. Final moisture contents for most end uses are below 30 percent, but a single-step schedule to achieve low moisture contents is impractical because of low drying rates at low moisture contents and low temperatures. Thus, multistep kiln schedules that progressively increase temperature and reduce EMC conditions are used. In this example, for simplicity of illustration, we chose a three-step schedule (Table 1).

In the first step of the schedule, the drying time to a final moisture content of 30 percent for each of the eight species is calculated using Equation (7). The average of these eight times is then calculated, and the mixture of the eight species is dried in this first step for that average time. A drying summary is given in Table 2. The drying time in this first step is 10.4 days and results in final moisture contents that range from 26.9 to 33.3 percent. These eight final moisture contents of the first step then become the initial moisture contents of the second step of the schedule. Again, the drying time from the initial moisture contents in this step to the 20 percent final moisture content of the step is calculated for all eight species and averaged, and the average drying time of 4.6 days is taken as the drying time for this step. The third step, from 20 to 10 percent moisture content, is developed in the same way and uses a drying time of 3.2 days. The total drying time from green to an average moisture content of 10 percent is 18.2 days.

Table 2 shows that the final moisture contents (target of 10 percent) range from 7.3 to 12.3 percent. This range is larger than would be desirable for most end uses. Thus, an equalizing period can be applied to reduce the range. If we specify that the final range should be between 9 and 11 percent moisture content and assume that Equation (7) applies to adsorption as well as drying (desorption), we can calculate the time required for equalizing. In this example, we calculate the time required for each of the eight species either to increase moisture content from below 9 percent to 9 percent or to decrease moisture content from above 11 percent to less than 11 percent. We then picked the longest of these times, 2.8 days (Table 3), as the equalizing time. The range of

Table 2—Summary of three-step kiln schedule for 1.125-in.- (29-mm-) thick lumber

Temperature (°F (°C))	EMC[a] (percent)	Target MC[b] (percent)	Specific gravity	Initial MC (percent)	Time[c] (days)	Final MC dried for average time (percent)
First step						
100 (38)	14	30	0.40	120	9.38	26.9
			0.50	90	9.59	27.9
			0.53	110	11.66	33.3
			0.61	90	11.60	32.7
			0.68	65	9.57	28.4
			0.75	70	11.35	31.7
			0.88	61	11.34	31.4
			0.93	50	8.99	28.0
Average					10.43	
Second step						
120 (49)	12	20	0.40	26.9	2.18	16.0
			0.50	27.9	2.98	17.6
			0.53	33.3	4.48	19.9
			0.61	32.7	4.98	20.7
			0.68	28.4	4.17	19.5
			0.75	31.7	5.74	21.6
			0.88	31.4	6.57	22.5
			0.93	28.0	5.42	20.9
Average					4.57	
Third step						
160 (71)	6	10	0.40	16.0	1.44	7.3
			0.50	17.6	2.06	8.2
			0.53	19.9	2.55	8.9
			0.61	20.7	3.05	9.8
			0.68	19.5	3.16	10.0
			0.75	21.6	3.89	11.1
			0.88	22.5	4.70	12.3
			0.93	20.9	4.61	12.0
Average					3.18	
Total drying time 18.2 days						

[a]EMC is equilibrium moisture content.
[b]MC is moisture content.
[c]Time required to dry from initial to target moisture content.

final moisture contents thus reduces from 9.6 to 11.0 percent moisture content. The total drying plus equalizing time is 21.0 days.

A similar analysis for 2.25-in.- (57-mm-) thick lumber is shown in Figure 3 and Tables 4 and 5. Total estimated drying time is 50.4 days, and total drying plus equalizing time is 58.6 days.

The model and method of segregation described here have not yet been tested in kiln drying studies. Research is necessary to do that, and is planned for the future. The basic experimental approach suggested is to collect additional experimental data to verify the relationship between drying time and specific gravity, initial moisture content, temperature, equilibrium moisture content, and thickness on a group of species that has a wide range of specific gravity and initial moisture content. Following that, groupings should be made according to the predictions of the model and kiln tests conducted to vary quality and uniformity of final moisture contents.

Concluding Remarks

A mathematical model was applied to the problem of grouping mixtures of species for drying so that all species in the group would emerge from the kiln at the same time within set limits of final moisture content and with minimum drying defects. The model correlates the drying time of lumber to specific gravity, initial moisture content, thickness, final moisture content, temperature, and the equilibrium moisture content conditions in the kiln. Specific gravity and initial moisture content are identified as the most important, available, and usable factors on which to group species. The equations of the model can be used to calculate combinations of specific gravity and initial moisture content that have equal drying times, and that is the basis for the groupings. The model can be used to calculate multistep drying schedules that will minimize the range of final moisture contents after drying.

A FORTRAN computer program is available for making the calculations shown in Tables 2 to 5 and printing the results in that format. The program can accommodate multiple species and schedule steps. A listing of the program can be obtained from William T. Simpson, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53705–2398, USA.

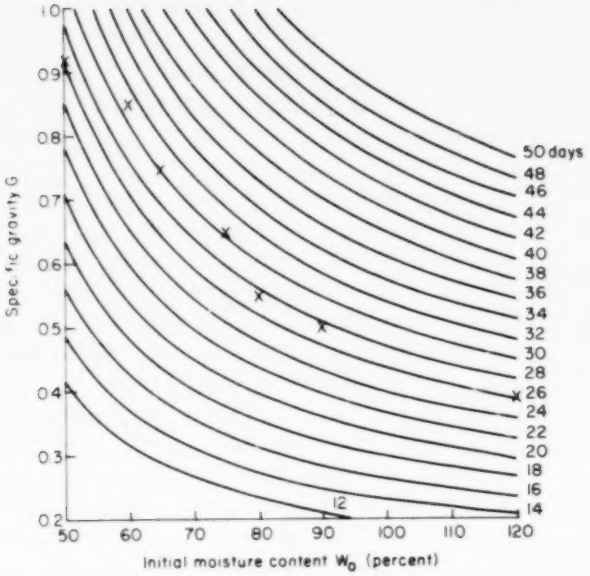

Figure 3 — Combinations of specific gravity and initial moisture content that result in equal drying times for 2.25-in.- (57-mm-) thick lumber at 100°F (38°C). (Final average moisture content, W_a = 30 percent; EMC, W_e = 14 percent.) (ML89 5654)

Table 3—Summary of equalizing period for 1.125-in.- (29-mm-) thick lumber

Temperature (°F (°C))	EMC[a] (percent)	Target MC[b] (percent)	Specific gravity	Initial MC (percent)	Equalizing times to 9 or 11 percent MC (days)	Equalizing time[c] (days)	Final MC distribution (percent)
160 (71)	10	10	0.40	7.3	1.55	2.80	9.6
			0.50	8.2	1.10	2.80	9.6
			0.53	8.9	0.12	2.80	9.7
			0.61	9.8	0.00	2.80	9.9
			0.68	10.0	0.00	2.80	10.0
			0.75	11.1	0.34	2.80	10.4
			0.88	12.3	2.80	2.80	11.0
			0.93	12.0	2.44	2.80	10.9

Total drying plus equalizing time 21.0 days

[a]EMC is equilibrium moisture content.
[b]MC is moisture content.
[c]Time required to dry from initial to target moisture content.

Table 4—Summary of three-step kiln schedule for 2.250-in.- (57-mm-) thick lumber

Temperature (°F (°C))	EMC[a] (percent)	Target MC[b] (percent)	Specific gravity	Initial MC (percent)	Time[c] (days)	Final MC dried for average time (percent)
First step						
100 (38)	14	30	0.39	120	26.24	27.1
			0.47	115	30.63	31.7
			0.50	105	30.67	31.6
			0.55	80	27.40	28.8
			0.65	75	30.36	31.0
			0.75	65	30.12	30.7
			0.85	60	30.87	31.1
			0.92	50	25.52	28.3
Average					28.98	
Second step						
120 (49)	12	20	0.39	27.1	6.22	16.2
			0.47	31.7	10.52	18.7
			0.50	31.6	11.13	19.1
			0.55	28.8	10.05	18.6
			0.65	31.0	13.80	20.6
			0.75	30.7	15.53	21.4
			0.85	31.1	17.85	22.3
			0.92	28.3	15.80	21.2
Average					12.61	
Third step						
160 (71)	6	10	0.39	16.2	4.08	7.4
			0.47	18.7	6.05	8.4
			0.50	19.1	6.60	8.7
			0.55	18.6	7.01	9.0
			0.65	20.6	9.27	10.3
			0.75	21.4	11.04	11.3
			0.85	22.3	12.96	12.3
			0.92	21.2	13.28	12.3
Average					8.79	
Total drying time 50.4 days						

[a]EMC is equilibrium moisture content.
[b]MC is moisture content.
[c]Time required to dry from initial to target moisture content.

Table 5—Summary of equalizing period for 2.250-in.- (57-mm-) thick lumber

Temperature (°F (°C))	EMC[a] (percent)	Target MC[b] (percent)	Specific gravity	Initial MC (percent)	Equalizing times to 9 or 11 percent MC (days)	Equalizing time[c] (days)	Final MC distribution (percent)
160 (71)	10	10	0.39	7.4	4.24	8.22	9.6
			0.47	8.4	2.55	8.22	9.7
			0.50	8.7	1.46	8.22	9.7
			0.55	9.0	0.07	8.22	9.7
			0.65	10.3	0.00	8.22	10.1
			0.75	11.3	1.92	8.22	10.5
			0.85	12.3	7.65	8.22	10.9
			0.92	12.3	8.22	8.22	11.0
Total drying plus equalizing time 58.6 days							

[a]EMC is equilibrium moisture content.
[b]MC is moisture content.
[c]Time required to dry from initial to target moisture content.

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